

How to Detect ‘Decoupled’ Heavy Supersymmetric Higgs Bosons

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Heretofore neglected decay modes of heavy MSSM Higgs bosons into a variety of neutralino pairs may push the LHC discovery reach for these crucial elements of an extended Higgs sector to nearly the TeV-scale — if sparticle-sector MSSM input parameters are favorable. This is well into the so-called decoupling region [1], including moderate to low $\tan\beta$ values, where no known signals exist for said heavy Higgs bosons via decays involving solely SM daughter particles, and the lighter h^0 mimics the lone SM Higgs boson. While the expanse of the Higgs to sparticle discovery region is sensitive to a number of MSSM parameters, including in particular those for the sleptons, its presence is primarily linked to the gaugino inputs — in fact, to just one parameter, M_2 , if gaugino unification is invoked. Thus consideration of high *vs.* low M_2 realms in the MSSM should be placed on a par with the extensive consideration already given to high *vs.* low $\tan\beta$ regimes.

Pacs Nos.: 14.80.Cp, 12.60.Jv, 14.80.Ly, 13.85.Qk

Much effort has been devoted to finding Large Hadron Collider (LHC) signals for the quintet of Higgs bosons expected in the minimal supersymmetric standard model (MSSM) — the lighter CP -even h^0 , the heavier CP -even H^0 , the CP -odd A^0 , and the charged H^\pm pair — and to delineating the reaches of the various signal modes in terms of MSSM input parameters. Key among these have naturally been inputs affecting the tree-level Higgs sector, M_A and $\tan\beta$, and by far the best-known depiction of MSSM Higgs boson search projections is the plot of the discovery regions (d.r.’s) in the plane formed by M_A and $\tan\beta$. Most studies of such signatures, including all those shown in well-known renditions of this plot, neglect or exclude the possibility of Higgs boson decays into sparticles. The few studies that have investigated such sparticle decay modes [2,3] have focused almost exclusively on the four-lepton plus missing transverse energy (E_T^{miss}) signature

$$pp \rightarrow H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow 4\ell + 2\tilde{\chi}_1^0 \quad (1)$$

where $\ell = e, \mu$ and the $\tilde{\chi}_1^0$ ’s, the lightest supersymmetric particles (LSPs), are stable and generate the E_T^{miss} . Previous studies have also been restrictive in how the $\tilde{\chi}_2^0$ ’s decayed, assuming three-body decay modes with virtual Z^0 ’s or charged sleptons while neglecting the possibility of on-shell two-body decays.

The MSSM sparticle spectrum is certainly far richer in possibilities for Higgs boson decays, many of which

can also yield the same $4\ell + E_T^{\text{miss}}$ signature. And, as the masses of the Higgs bosons grow larger, ignoring such potential daughter states becomes increasingly ill-conceived. The present study is a first-ever serious examination of *all* possible decay chains leading from the production of a heavy neutral MSSM Higgs boson, H^0 or A^0 , to a $4\ell + E_T^{\text{miss}}$ final state [4]:

$$pp \rightarrow H^0, A^0 \rightarrow \tilde{\chi}_a^+ \tilde{\chi}_b^-, \tilde{\chi}_i^0 \tilde{\chi}_j^0 \rightarrow 4\ell + 2\tilde{\chi}_1^0 \quad (2)$$

($a, b = 1, 2, i, j = 1, 2, 3, 4$). In particular, decays including the heavier neutralino (and, to a lesser extent, chargino) states beyond $\tilde{\chi}_2^0$ are found to dominate the signal over significant swaths of the parameter space.

Naturally, no such signal would exist if the neutralino (and chargino) masses were not light enough for the Higgs bosons to decay into pairs of them. Yet for the heavy ($\gtrsim 500$ GeV) H^0 and A^0 being considered here it is in fact *un-natural* for such decay modes to be excluded. To address this question more quantitatively, the MSSM input parameters to the neutralino spectrum must be incorporated. These are, at tree-level (to which radiative corrections are very minor [5]): $\tan\beta$, the higgsino mixing parameter μ , and the soft supersymmetry (SUSY)-breaking $SU(2)_L$ and $U(1)_Y$ gaugino masses, M_2 and M_1 , respectively. Gaugino unification, which draws support from the projected merging of the $SU(2)_L$ and $U(1)_Y$ coupling strengths at the GUT scale in MSSM scenarios, imposes the TeV-scale relation $M_1 \simeq \frac{5}{3} \tan^2 \theta_W M_2$ [6]. Fig. 1 shows the inclusive production rate for $4\ell + E_T^{\text{miss}}$ events from LHC H^0 and A^0 production in the plane formed by μ and M_2 , for representative values of M_A and $\tan\beta$, and assuming an integrated luminosity of 300 fb^{-1} . The shape of such contours were found to be quite insensitive to values of $M_A \gtrsim 400$ GeV and $\tan\beta \gtrsim 5$, though rates tended to grow with decreasing M_A and increasing $\tan\beta$. If M_2 is not too large, dozens to hundreds of signal events are expected for all values of $|\mu|$, though lower $|\mu|$ values are certainly more favorable. Lower values of $|\mu|$ also enable large event rates for larger values of M_2 as shown. Also depicted is the percentage of signal events stemming from $H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ decays only. For values of $|\mu| \gtrsim 400$ GeV, this generally exceeds 90%. However, for lower values of $|\mu|$ and low to moderate M_2 values, decay modes featuring the other heavier neutralinos, $\tilde{\chi}_3^0$ and/or $\tilde{\chi}_4^0$, become dominant. The maxima for the signal event rate move deeper and deeper into this previously unana-

lyzed zone as M_A grows large. Thus the optimal low $|\mu|$ region was overlooked by previous studies limited to only the $H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ decay mode.

As the Higgs boson masses are raised and heavier neutralino states become kinematically accessible as decay products, it becomes ever more feasible to have slepton masses situated below the heavier neutralino masses. Neutralino decays to on-shell charged sleptons strongly enhance branching ratios (BRs) to leptonic final states, with virtually all such decays yielding leptons (which tend to be stiffer due to the heavier parent neutralino). Thus the heavier neutralinos may well differ significantly from $\tilde{\chi}_2^0$ in their capacities as conduits for the production of charged leptons from heavy Higgs boson production. Here though spoiler decay modes via on-shell sneutrinos must not dominate, since these lead to uninteresting neutrino-bearing final states. Fortunately this happens along relatively narrow strips in parameter space, such as when [7] $m_{\tilde{\nu}} < m_{\tilde{\chi}_2^0} < m_{\tilde{\ell}}$, a condition though that is quite compatible with early LHC sparticle detection. In this case the previously-studied $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ decay modes yield almost no signal events, while at the same parameter space point huge event rates from the thusfar neglected heavier neutralino channels are quite possible.

Full event generator-level studies including the simulation of a typical LHC detector environment (using private codes checked against results in the literature) were performed using HERWIG 6.5 [8] (which obtains its MSSM inputs from ISASUSY 7.58 [9]) with the CTEQ6L [10] set of parton distribution functions. Higgs bosons were generated through the sub-processes $q\bar{q}, gg \rightarrow H^0, A^0$, conservatively ignoring minor additional contributions from $2 \rightarrow 3$ subprocesses which would in any event tend to fail cuts imposed later. (The same HERWIG processes were used to normalize rates shown in FIG. 1.) Four-lepton events are first selected according to these criteria:

0. Events have exactly four leptons, $\ell = e$ or μ , consisting of two opposite-sign, same-flavor lepton pairs, meeting the following criteria: (i) each lepton must have $|\eta^\ell| < 2.4$ and $E_T^\ell > 7, 4$ GeV for e, μ , respectively; (ii) each lepton must be isolated, set by the demands that there be no tracks (of charged particles) with $p_T > 1.5$ GeV in a cone of $r = 0.3$ radians around a specific lepton, and also that the energy deposited in the electromagnetic calorimeter be less than 3 GeV for $0.05 \text{ radians} < r < 0.3 \text{ radians}$.

Selected events are then subjected to the following cuts:

- 1.** no opposite-charge same-flavor lepton pairs may reconstruct $M_Z \pm 10$ GeV.
- 2.** all leptons must have $20 \text{ GeV} < E_T^\ell < 80 \text{ GeV}$.
- 3.** events must have $20 \text{ GeV} < E_T^{\text{miss}} < 130 \text{ GeV}$.
- 4.** any jets (defined for $E_T > 20 \text{ GeV}$, $|\eta| < 2.4$ and with $\Delta R = 0.5$ [11]) must have $E_T^{\text{jet}} < 50 \text{ GeV}$.

An additional cut on the four-lepton invariant mass was also examined; however, the optimal numerical value for this cut depends on the masses of the Higgs bosons and the LSP, which are assumed to be *a priori* unknown. If these masses are known, even approximately, then this

extra cut, not employed here, can certainly further reduce the background rates.

All noteworthy background processes were simulated, including those from Standard Model (SM) processes $Z^0 Z^{0(*)}$ and $t\bar{t} Z^{0(*)}$ and MSSM ones involving $\tilde{\ell}$ and/or $\tilde{\nu}$ pair production, $\tilde{\chi}\tilde{\chi}$ or $\tilde{q}/\tilde{g}\tilde{\chi}$ pair production (here the neutralinos and/or charginos are produced via an s -channel off-shell Z^{0*} or $W^{\pm*}$), \tilde{q} and/or \tilde{g} pair production (here leptons are generated via subsequent cascade decays featuring charginos and neutralinos, see [12], but the jet cut is effective at eliminating such events, assuming reasonably heavy colored sparticles with masses well above those of the colorless EW states), $t\bar{t}h^0$, and $tH^- + \text{c.c.}$ (this last process, studied in [13], could arguably be lumped together with the signal processes; however, the cuts employed here are not designed to select such events, with at best only a handful of these surviving).

Information gathered from FIG. 1 enables selection of representative MSSM input parameter sets, aside from M_A and $\tan\beta$, for the uncolored sparticles (colored gluinos and squarks are fixed around the TeV scale). For this work, one set is chosen to have $4\ell + E_T^{\text{miss}}$ events coming almost exclusively from $H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ decays:

Set 1: $M_2 = 180 \text{ GeV}$, $M_1 = 90 \text{ GeV}$, $\mu = -500 \text{ GeV}$, $m_{\tilde{\ell}_{\text{soft}}} = m_{\tilde{\tau}_{\text{soft}}} = 250 \text{ GeV}$;

while for a second set channels involving the heavier neutralinos tend to dominate:

Set 2: $M_2 = 200 \text{ GeV}$, $M_1 = 100 \text{ GeV}$, $\mu = -200 \text{ GeV}$, $m_{\tilde{\ell}_{\text{soft}}} = 150 \text{ GeV}$, $m_{\tilde{\tau}_{\text{soft}}} = 250 \text{ GeV}$.

Here $m_{\tilde{\ell}_{\text{soft}}}$ and $m_{\tilde{\tau}_{\text{soft}}}$ are SUSY-breaking slepton mass inputs, with $m_{\tilde{\ell}_{\text{soft}}} \equiv m_{\tilde{\ell}_R} = m_{\tilde{\ell}_L}$, to which the physical slepton masses are closely linked [12], and $A_\tau = A_\ell = 0$. Signal(S) and background(B) rates for each parameter set are studied across the $(M_A, \tan\beta)$ plane to map out potential d.r.'s. The exact criteria used for demarcating d.r.'s are presence of at least 10 S events and a 99%-confidence-level upper limit on B events below the 99%-confidence-level lower limit on S+B events [14]. (As the number of S events grows large, this merges with the typical $S/\sqrt{B} \gtrsim 4\text{-}5$ criterion.) Simulation runs at well over a thousand points in the $(M_A, \tan\beta)$ plane yield the results shown in FIG. 2 and FIG. 3 (detailed tabular results from representative simulation runs will be presented elsewhere) for **Set 1** and **Set 2**, respectively. The $4\ell + E_T^{\text{miss}}$ d.r.'s for LHC luminosities of $\mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1}$ and 300 fb^{-1} are delineated by the thickened contours, with the 100 fb^{-1} contours inscribed within the 300 fb^{-1} ones. Also shown are the region excluded by LEP results and the the expected reaches, assuming $\mathcal{L}_{\text{int}} = 300 \text{ fb}^{-1}$, of Higgs boson decay modes into SM daughter particles as developed by the ATLAS collaboration [15]. The new $4\ell + E_T^{\text{miss}}$ d.r.'s clearly provide significant coverage of the moderate $\tan\beta$, high M_A so-called 'decoupling region' [1] inaccessible to the other signals [15–17]. Certainly, the Higgs boson to SM daughters' d.r.'s taken from the ATLAS results are not obtained using the same choice of MSSM

input parameters as are the $H^0, A^0 \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$ ones developed in the present work. In fact, the former d.r.'s use input choices designed to eliminate, or at least minimize, Higgs boson decays into sparticles. This means that, were the ATLAS reaches to be generated for the same set of neutralino input parameters as the $H^0, A^0 \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$ discovery regions, the former may well *shrink* in size, further emphasizing the importance of thoroughly studying the $H^0, A^0 \rightarrow 4\ell + E_T^{\text{miss}}$ signature. The diminution of the expected signatures from SM decay modes of the MSSM Higgs bosons was investigated in [2,17]. Assumptions inherent in the ATLAS d.r.'s for the SM decay modes of the MSSM Higgs bosons are no less restrictive than the choices of MSSM input parameters made to generate the two $4\ell + E_T^{\text{miss}}$ d.r.'s in this work.

Comparing d.r.'s for **Set 1** and **Set 2**, startling differences are immediately apparent (these will be described in more detail elsewhere [18]). Of perhaps foremost importance among these is **Set 2**'s far greater stretch to high M_A values. This is due to the heavier neutralino decay modes first described herein: in FIG. 3 corresponding to **Set 2**, inclusion of only $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ decay modes, as in previous studies, yields a mere smidgen of a d.r. around $(M_A, \tan\beta) = (350\text{--}400\text{ GeV}, 3\text{--}4.5)$ rather than the expansive region shown. All of the large portion of the d.r. above $\tan\beta = 5$ would be lost. Note how there is some d.r. reach for almost all possible values of $\tan\beta$, demonstrating the relative merit of the M_2 and μ parameters in demarcating heavy Higgs bosons' d.r.'s. Previously, particular attention to the high $\tan\beta$ regime of the MSSM has been afforded in this journal [19]. It should however be noted that the parameter choices considered herein are no more limited in scope than studies devoted exclusively to that subset of model parameter space. Indeed, artificially foisting sparticle masses into the stratosphere to avoid their presence in Higgs boson decays, as is the norm in most MSSM Higgs boson studies (which then resemble two-Higgs doublet model studies) is arguably even more restrictive. For all their differences, roughly representing different extremes in the signal composition, both **Set 1** and **Set 2** offer new coverage for the crucial moderate to high M_A , middle $\tan\beta$ zone.

In conclusion, restricting the search for heavy MSSM Higgs boson LHC signals to SM decay modes plus perhaps the single neutralino pair $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ misses a significant portion of the potential d.r. accessible with the inclusion of all sparticle decays. A complete analysis featuring all sparticle channels yielding the $4\ell + E_T^{\text{miss}}$ signature is quite tractable, and, for the heavy H^0 and A^0 present in the so-called decoupling region, (i) this is the *only* known signal mode; and (ii) most of the discovery region mapped out relies on the heavier neutralinos, which also more easily accommodate rate-enhancing underlying sleptonic states, never included in such analyses before.

We are grateful to Dr. F. Moortgat for providing codes modified for use in this project, and to Dr. S. Moretti for his critical reading of the manuscript. G. Bian, Y. Liu and M. Ruan provided valuable assistance with graphics. The work of MB is partially funded by a

National Science Foundation of China grant (No: 9417188).

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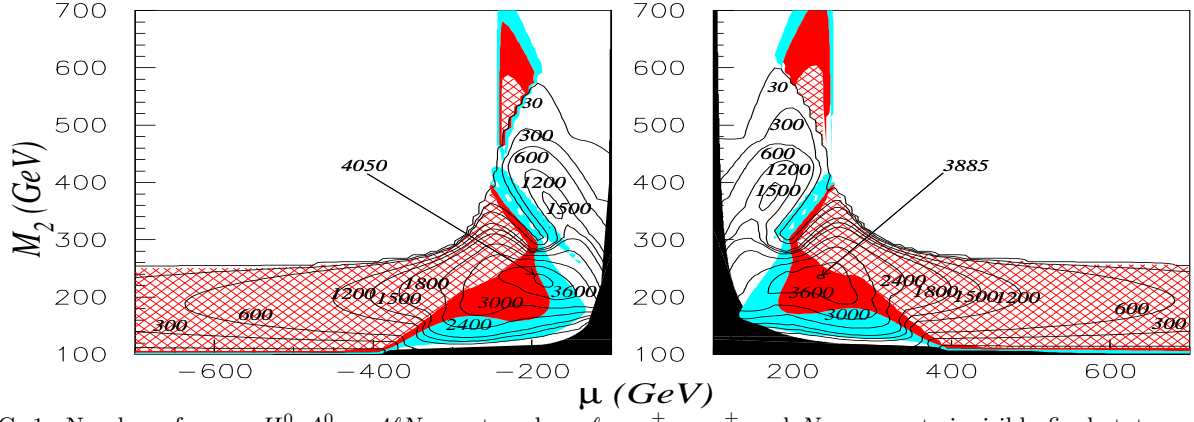


FIG. 1. Number of $pp \rightarrow H^0, A^0 \rightarrow 4\ell N$ events, where $\ell = e^\pm$ or μ^\pm and N represents invisible final state particles, for 300 fb^{-1} , with $\tan\beta = 10$ and $M_A = 500 \text{ GeV}$. Also shown is the percentage from $H^0, A^0 \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ (in color / black & white): $> 90\%$ (red cross-hatched / grey cross-hatched), $50\% - 90\%$ (red/dark shaded), $10\% - 50\%$ (blue/lighter shading), $< 10\%$ (white/no shading). Optimized slepton masses [13] (with stau inputs raised 100 GeV) are used, $m_t = 175 \text{ GeV}$, $m_b = 4.25 \text{ GeV}$, $m_{\tilde{q}} = 1 \text{ TeV}$, $m_{\tilde{g}} = 800 \text{ GeV}$, $A_\tau = A_t = 0$. The blackened-out areas are excluded by LEP.

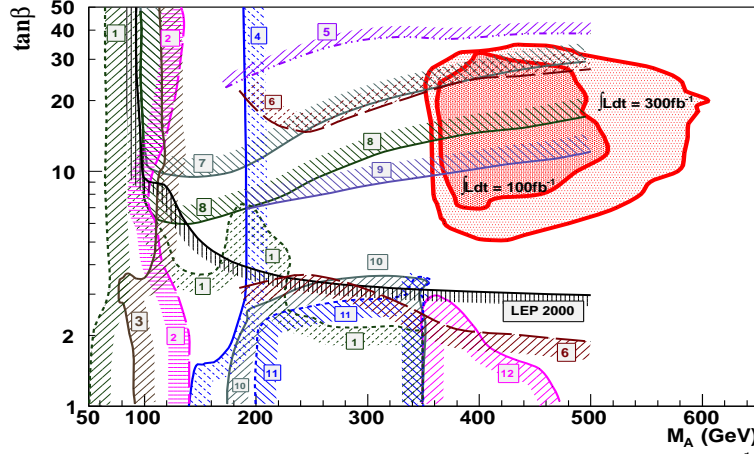


FIG. 2. Discovery region in $(M_A, \tan\beta)$ plane for MSSM Parameter **Set 1** and $\mathcal{L}_{int} = 100 \text{ fb}^{-1}$ & 300 fb^{-1} for MSSM Higgs bosons' 4ℓ signals from their $\tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_m^+ \tilde{\chi}_n^-$ decays (here H^0, A^0 decays to $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ totally dominate), shown together with regions for other MSSM Higgs boson signatures from decays to SM particles based upon LEP results and ATLAS simulations [15] (which assume $\mathcal{L}_{int} = 300 \text{ fb}^{-1}$) where labels represent: 1. $H^0 \rightarrow Z^0 Z^{0*} \rightarrow 4\text{leptons}$; 2. $t \rightarrow bH^+, H^+ \rightarrow \tau^+ \nu + \text{c.c.}$; 3. $t\bar{t}h^0, h^0 \rightarrow b\bar{b}$; 4. $h^0 \rightarrow \gamma\gamma$ and $W^\pm h^0/t\bar{t}h^0, h^0 \rightarrow \gamma\gamma$; 5. $b\bar{b}H^0, b\bar{b}A^0$ with $H^0/A^0 \rightarrow b\bar{b}$; 6. $H^\pm \rightarrow t\bar{b} + \text{c.c.}$; 7. $H^0/A^0 \rightarrow \mu^+ \mu^-$; 8. $H^0/A^0 \rightarrow \tau^+ \tau^-$; 9. $g\bar{b} \rightarrow \bar{t}H^+, H^+ \rightarrow \tau^+ \nu + \text{c.c.}$; 10. $H^0 \rightarrow h^0 h^0 \rightarrow b\bar{b}\gamma\gamma$; 11. $A^0 \rightarrow Z^0 h^0 \rightarrow \ell^+ \ell^- b\bar{b}$; 12. $H^0/A^0 \rightarrow t\bar{t}$. Note that SM discovery regions are not for the same input parameters: they presume Higgs bosons cannot decay into sparticles, so more accurate estimates may well be smaller.

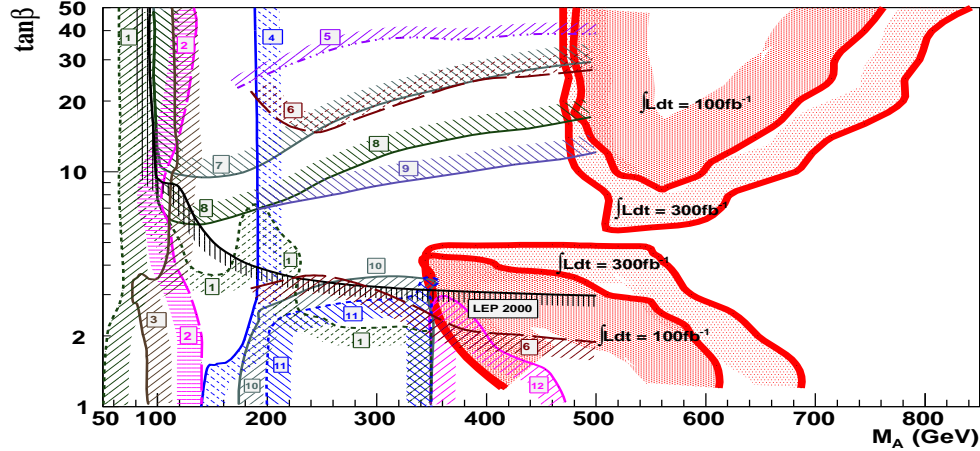


FIG. 3. Discovery region in $(M_A, \tan\beta)$ plane for for MSSM Parameter **Set 2** and $\mathcal{L}_{int} = 100 \text{ fb}^{-1}$ & 300 fb^{-1} for MSSM Higgs bosons' 4ℓ signals from their $\tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_m^+ \tilde{\chi}_n^-$ decays (here Higgs boson decays to higher-mass neutralinos typically dominate), shown together with regions for MSSM Higgs boson signatures from decays to SM particles as in FIG. 2.